Modeling and Managing the Ohio River

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Abstract

The Great Lakes and Ohio River Division (LRD) Water Management Team of the U.S. Army Corps of Engineers now has 20 years of operational experience in using an unsteady flow model for managing the Ohio River. The model, called Cascade, is a valuable and effective tool in determining the impact of reservoir releases on flood levels, modeling the effects of lock and dam operations during low flows, and forecasting river stages and flows in support of Corps flood management and navigation missions. Cascade is a fully implicit model using finite difference approximations of the one-dimensional Saint Venant equations. It is unique among other existing unsteady flow models as it is a fully object-oriented program written in C++ composed of a hierarchy of object classes referenced by a system of linked lists. Additionally, the model operates as a client in the context of a data server. The physical system modeled by Cascade includes the Ohio River, portions of the upper and lower Mississippi River, and 11 major and 9 minor tributaries. The model includes 21 locks and dams and local runoff is input at 53 locations. An overview of the model will be presented with examples of its application to Ohio River management during high and low flow conditions.

Introduction

The Ohio River drains America's heartland, stretching more than 981 miles from Pittsburgh, PA to Cairo, IL where it joins the Mississippi River. Its 204,000 mi^2 watershed stretches north to south from New York to Alabama and east to west from Pennsylvania to Illinois. 14 major tributaries and 11 minor tributaries supply the river, along with runoff from 43,490 mi^2 of local drainage area. Ohio River flows vary over three orders of magnitude at its confluence with the Mississippi River. Flows at the outlet (1933 to 1999) range from a low of about 425 m^{3}s^{-1} (15,000 cfs) to the 1937 flood peak of about 52,380 m^{3}s^{-1} (1,850,000 cfs) and have an annual average of 7,500 m^{3}s^{-1} (265,000 cfs) (unpublished USACE computed flows).

The Ohio River has been extensively modified to support inland navigation (Robinson 1983). In its original state, the unfettered river was primarily navigable only by canoe and flatboat. Natural snags of timber debris, shoals, and shallow depths made it unnavigable by larger and deeper draft boats except during periods of high flow. Natural falls and rapids at Louisville, Kentucky presented a significant obstacle. Channel improvements began by the Corps of Engineers in 1824 through 1861 with the removal of snags and dredging of shoals. By 1929, 50 wicket dams with locks provided a 9 foot navigation depth throughout the river's length. A navigation modernization program began in 1954 with the goal of replacing the 50 low lift dams with 20 high lift dams. With the construction of Olmstead Lock and Dam, and removal of the two remaining low lift wicket dams (52 and 53), the modernization will be complete. Olmstead's design is a modern rendition of the wicket dams. With the exception of Dashields, all of the other dams are fixed concrete weirs with moveable gates. Due to the navigation structures, the river's profile is that of a staircase during low to moderate flows. As flows increase, the dams' gates are opened. At high flows, the dams' gates are fully opened and a natural river profile returns. The navigation structures do not afford any flood control. Figure 1 illustrates the river's profile.

Figure 1. The Ohio River profile

Need for Dynamic Routing

The LRD Water Management Team has several responsibilities related to Ohio River management. The Team is responsible for reducing water level stages along the lower Ohio and middle Mississippi Rivers during significant flood events, producing and issuing daily USACE internal river flow and stage forecasts and coordinating public National Weather Service river forecasts, issuing low flow guidance, coordinating interagency (Tennessee Valley Authority and USACE) flows for lower Ohio River safety concerns during lock and dam operation and maintenance, providing flow characteristics for real time spill monitoring, and computing mainstem flood reduction benefits for the Annual Flood Damage Report (AFDR) to Congress. To conduct these responsibilities, the Team must know the detailed hydrologic and hydraulic conditions of the watershed and its river, and be able to produce a reliable near-term (3-5 day) forecast of river conditions. In support of the AFDR, river hydraulic simulations are required to compute benefits and to assign them to the appropriate Districts and respective projects. Because of the river's complex hydraulics (staircased pools at low to moderate flows, Mississippi River and tributary backwater effects, overbank flow at high flows, dynamic tributary and local inflows, and flow fluctuations due to lock and dam operations and reservoir peaking and ponding), traditional hydrologic routing techniques are insufficient to accurately model and forecast the river dynamics. Hydrodynamic modeling is required, conducted on a daily basis at an hourly computational timestep.

As early as 1971, the use of dynamic routing (numerical modeling of unsteady flow) was explored as a joint effort between the Waterways Experiment Station and the Ohio River Division (Johnson 1982). An explicit finite difference scheme was used to build a model of the lower Ohio River and its junction with the Mississippi River. This early model was then replaced by a model that treated the major tributaries as dynamic branches of the system and the channel geometric data was improved. This model, named the SOCHMJ for Simulation of Open Channel Hydraulics in Multi-Junction Systems, was implemented operationally by the Ohio River Division in 1974. The model represented the lower Ohio River from Golconda to Cairo, IL and its junction with the Mississippi River from Thebes, IL to Caruthersville, MO. The Cumberland and Tennessee Rivers were included as dynamic tributaries downstream of their respective Barkley and Kentucky Dams. At that time, the SOCHMJ solution scheme was computationally expensive with respect to the available computer technology but proved to be a valuable tool for flood control operations. The desire to expand the model upstream resulted in the addition of a capability to handle the high-lift locks and dams and implementation of an implicit finite difference solution scheme adopted from Chen (1973). This new model also incorporated sediment transport and was christened FLOWSED (Johnson 1982). FLOWSED was delivered to the Ohio River Division in 1981. To make the model computationally efficient, the sediment transport numerics were dropped from the model, and the model was modified to fit into an operational context. The modified model was placed in operation during October 1983. In 1985, use of the SOCHMJ model was discontinued and FLOWSED became the primary model for routing Ohio River flows from Pittsburgh, PA to Cairo, IL. The utility of the model soon proved itself, and it became the primary operational tool. During 2000, the FLOWSED model was re-developed by Mr. Stan Wisbith using the C++ programming language, replacing the Fortran 77 version. The new model became operational in the early fall of 2000 and was dubbed Cascade. Cascade was designed to be 'plug compatible' with FLOWSED, using the same input/output format and based on the same finite difference equations, providing for continuous simulation capabilities since 1983.

The physical system modeled by Cascade includes approximately 2,600 km (1,616 mi) of rivers. The main stem portion is comprised of 1,580 km (982 mi) of the Ohio River (Pittsburgh, PA to Cairo, IL) and 173 km (107 mi) of the lower Mississippi River (Cairo, IL to Caruthersville, MO). Tributaries include 70 km (44 mi) of the upper Mississippi River (Thebes, IL to Cairo, IL) and 777 km (483 mi) of other tributaries. Included in the model are 21 locks and dams; 20 on the Ohio River and 1 on the Kanawha River in West Virginia. There are 12 major tributary rivers, including the upper Mississippi River, and 9 minor tributaries. Figure 2 illustrates the modeled river system. In addition, local runoff is input at 53 locations. The model uses 403 computational points or 'nodes' with an average distance between nodes of approximately 8 km (5 mi). The time step used by Cascade is 1 hour.

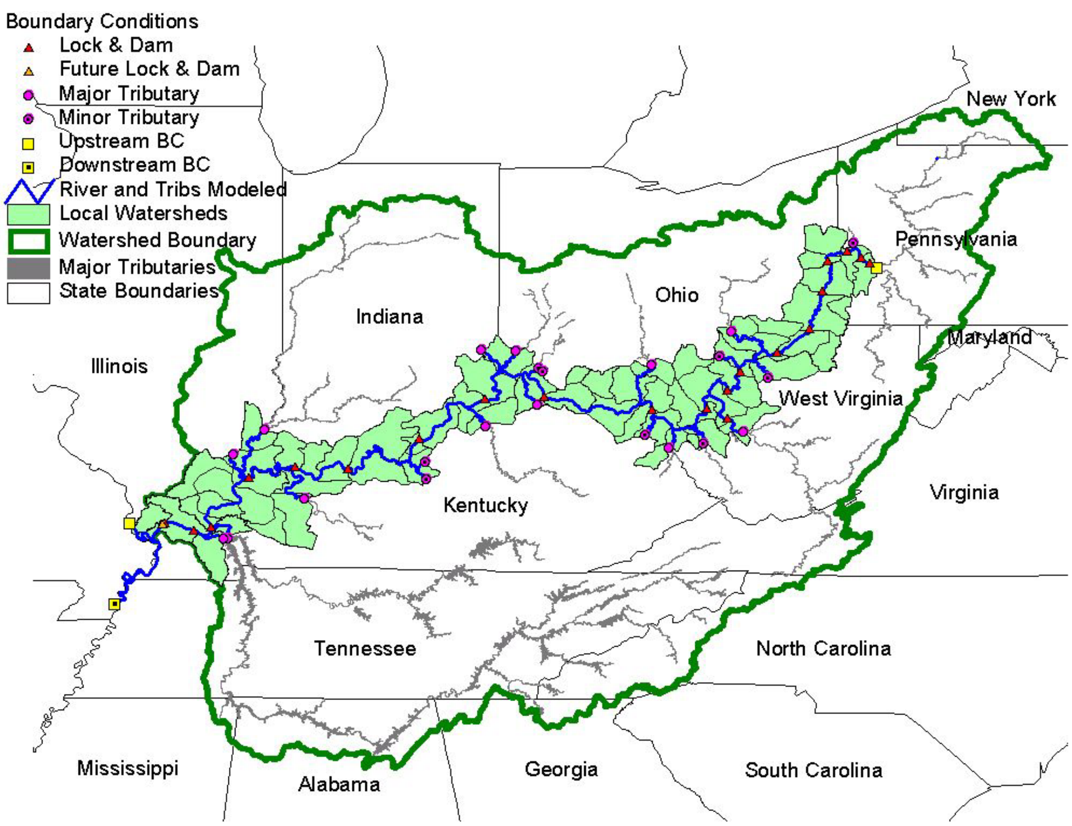

Figure 2. Physical system modeled by Cascade

Overview of Cascade

Finite difference representation and solution scheme. Cascade is a fully implicit model using finite difference approximations of the one-dimensional Saint Venant differential equations for the conservation of mass and momentum:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q_{\inf low}+q_{levee}+q_{floodplain}$$

$$\frac{\partial(\rho Q)}{\partial t}\Delta x=\frac{\partial\left(\beta\rho Q^2/A\right)}{\partial x}\Delta x-\rho q\frac{Q}{A}\Delta x+\sum forces$$

The finite difference representation used in Cascade is the same as that used in FLOWSED and was originally described by Chen (1973). Where Φ represents the functions of the dependent variables Q (flow) and Y (the channel cross section area A is expressed as a function of river depth Y), the value and partial derivative of Φ are expressed as

$$\phi\cong\frac{\phi_i^n+\phi_{i+1}^n}{2}$$

$$\frac{\partial\phi}{\partial x}\cong\frac{\phi_{i+1}^{n+1}-\phi_i^{n+1}}{\Delta x}$$

$$\frac{\partial\phi}{\partial t}\cong\frac{1}{2\Delta t}\left[\left(\phi_i^{n+1}-\phi_i^n\right)+\left(\phi_{i+1}^{n+1}-\phi_{i+1}^n\right)\right]$$

The upper subscript represents the position within the computational cell with respect to time n, and the lower subscript represents the position with respect to space (node i). The end of timestep evaluation has proved to be both stable and accurate due to the 1 hour timestep and the relatively slow rate of change on the Ohio River.

After applying the finite difference representations to the Saint Venant equations, rearranging terms and collecting coefficients, there is a pair of linear equations for each sub-reach between every two locations or "nodes" that define the model for each time step. Every pair of equations has four unknowns, depth and flow, at the end of the time step for each of the adjacent nodes. That is, at time n+1 for nodes i and i+1, the unknowns in the linear equations are depth at the end of the time step, Y_i^{n+1} and Y_{i+1}^{n+1}, and the flows, Q_i^{n+1} and Q_{i+1}^{n+1}. The known terms are collected into coefficients valid only for the specified node pair at a particular time and particular location (coefficient formulation varies from that of internal node pairs at boundaries and junctions). The generalized form of the linear equations for each node pair i and i+1 is:

$$C_{1,1}\,Y_i^{n+1}+C_{1,2}\,Q_i^{n+1}+C_{1,3}\,Y_{i+1}^{n+1}+C_{1,4}\,Q_{i+1}^{n+1}=E_1$$
$$C_{2,1}\,Y_i^{n+1}+C_{2,2}\,Q_i^{n+1}+C_{2,3}\,Y_{i+1}^{n+1}+C_{2,4}\,Q_{i+1}^{n+1}=E_2$$

where the coefficients are represented as $C_{j,k}$ an E_j, j referencing either the first (j=1) or second (j=2) equation and k the specific coefficient (k=1, 2, 3, 4). The addition of known boundary conditions in the form of known flows or depths allow this system of equations to be solved using the double sweep algorithm (Chen 1973) rather than complete matrix inversion. On the downstream sweep at time n+1, the known upstream boundary condition enables the linear equations to be reduced to two unknowns. On the successive upstream sweep, the known downstream boundary condition allows for the solution of the remaining unknown at each node. The double sweep algorithm uniquely lends itself to object-oriented C++ programming structures, computational efficiency, and a highly stable solution.

Object-oriented coding. Cascade is unique among other existing unsteady flow models as it takes advantage of the C++ language object-oriented programming elements, especially user-defined data types, classes that encapsulate the data representations, exception handling, and inheritance. It is composed of a hierarchy of classes referenced by a system of linked lists. The linked lists contain pointers to neighboring computational elements (nodes, reaches, and pools) creating model topology (i.e., each element knows its location relative to its upstream and downstream neighbors). Computations progress along the system of lists in a semi-autonomous manner. This arrangement provides an organizational and computational system that is much more flexible than the traditional matrix methods and permits the model to be self-configuring. The resulting model structure very closely parallels an actual river system. Indeed, the model is literally 'built' each time it is run, based upon input configuration files, then reconfigures itself during the computational process as locks and dams go in and out of operation during moderate to high flow events. Figure 3 illustrates the system object organization map. Additionally, the model operates as a client in the context of a data server. The model communicates with its databases through the data server to request, store, and pre- and post-process modeled and observed data.

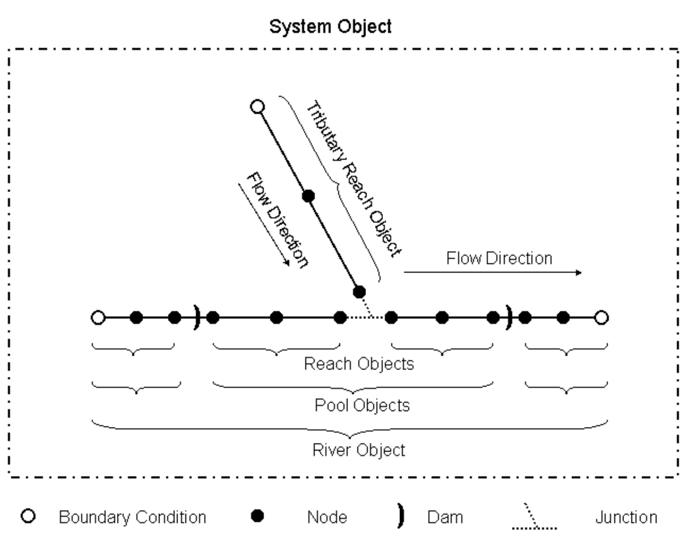

Figure 3. System object organization map

Node class. The *node* class is the basic class of objects used by the model. Objects of this class contain all the variables and procedures relative to a single location (cross section) or node on the river. This includes such variables as flow, water surface elevation, channel depth, and geometry tables. Also contained in this class are variables pertinent to the sub-reach between a node and the next upstream node. That is, the object for node 2 would contain the variables for the sub-reach from node 1 to node 2. These variables include the distance between nodes, the lateral inflow, and the abstracted flood plain area.

Reach class. The next higher class of objects in the model is the *reach*. A reach is defined as a section of river bounded by an upstream and downstream external or internal boundary condition. Included within this class is a linked list of the nodes forming this particular reach. This list is ordered from upstream to downstream. The first node is an upstream boundary, a dam tailwater node or the first node downstream from a junction with a tributary. The last node is a downstream boundary, a dam headwater node or the last node upstream of a tributary junction. A minimum of three nodes per reach is required.

Pool class. The main operating class of objects in the model is the *pool*. The pool class contains the procedures to model control structures such as dams or weirs. A pool is defined as the portion of a stream bounded by an external boundary or a dam. This class contains two linked lists of reach objects. The first contains the reaches forming the main river. This is referred to as the mainstem list. As with the nodes, the reaches in this list are ordered from upstream to downstream. The second list contains the tributary reaches that join with the river within the pool. This list is referred to as the tributary list. This list is arranged in the order that the tributaries join the main river moving in a downstream direction. That is, the first reach in the mainstem list is assumed to join with the first reach in the tributary list and with the second reach in the mainstem list at a junction. The second mainstem reach and the second tributary reach join with the third mainstem reach at a junction, and so forth. A minimum of one mainstem reach is required.

The first mainstem reach would either be at an upstream boundary or just downstream of a dam. The last mainstem reach would be either just upstream of a dam or at a downstream boundary. Each tributary reach would normally start at an upstream boundary. However it is possible to have the upstream end of a tributary reach connect to the downstream end of another river system. No tributary reaches are required. However from the previously described relationship, there must be one more mainstem reach than there are tributary reaches. A minimum pool configuration would consist of only one reach, this being on the mainstem list.

River class. The *river* object class is primarily an organizing object. This class contains a linked list of pools in the river. The pools in this list are ordered in the downstream order. The first pool would normally begin at an upstream boundary. The last pool of the main river would normally end at a downstream boundary. Rivers connecting to a tributary reach of another river would end at a control structure or false dam. Only one pool is required per river.

System class. The *system* class of objects is the highest class and is used only as a container to hold river objects. This class contains a linked list of river objects.

The first river in the list is assumed to be the main river in the entire system. Although it is not strictly necessary, it is recommended that tributary rivers be defined in the upstream direction. The model will compute the last river in the list first, then continue to move up the list. Ordering the rivers in an upstream direction slightly reduces the computation time.

Boundary and initial conditions and daily operations. Boundary data for the model is comprised of main stem, local and tributary inflows and headwater elevations at each of the 21 locks and dams. The main stem and tributary information is received from 4 of the Division's district offices (Pittsburgh, Huntington, Louisville and Nashville) as well as from the Tennessee Valley Authority and the National Weather Service North Central River Forecast Center. The Team computes the local runoff using a simplified runoff model and daily precipitation. The initial conditions (water surface elevations, channel flows and lateral inflows) required by the unsteady flow model are obtained by making a hindcast or 'update' run. Starting conditions from the last previous update run are first retrieved from the system database. Then observed boundary conditions are used to run the model to current time. This establishes current conditions at all nodes. The system state is then saved back into the system database to be used by the forecasting step and the next day's update run. The next step of the daily operation is the forecast run. The forecast run uses the previously computed system states as initial conditions, and uses forecasted boundary data to produce the forecast river stages and flows.

Model Application

High flows. During significant flood events on the lower Ohio and middle Mississippi Rivers, the Team directs flow releases from Barkley Lake on the Cumberland River and issues regulation instructions to the Tennessee Valley Authority for the operation of Kentucky Lake on the Tennessee River. As needed, the Team also coordinates flood control operations of other Corps reservoirs located in the Ohio River watershed (78 reservoirs in all). Cascade is used to determine the impact of trial reservoir releases on flood levels and to determine the expected magnitude and timing of the Ohio River flood crest. The model has proved to be an invaluable tool in this respect. The effect of the flood operation is to increase Ohio River flows and stages above natural conditions on the rising and falling limbs of the flood hydrograph but to reduce peak flows and stages during the crest, as illustrated in Figure 4. Lee et al. (2002) describe the Team's flood management operations in detail.

The Team computes Ohio River stage reductions and prevented damages (lower Ohio and middle Mississippi Rivers) using stage-damage relationships and the routing of regulated and natural flows. As mandated by the Energy and Water Appropriation Act of 1984, these values are reported annually to Congress. During the period 1984 through 2002, flood stages have been reduced a maximum of 2.68 feet with total prevented damages of $365,399,000 due solely to the operation of Kentucky and Barkley Lakes.

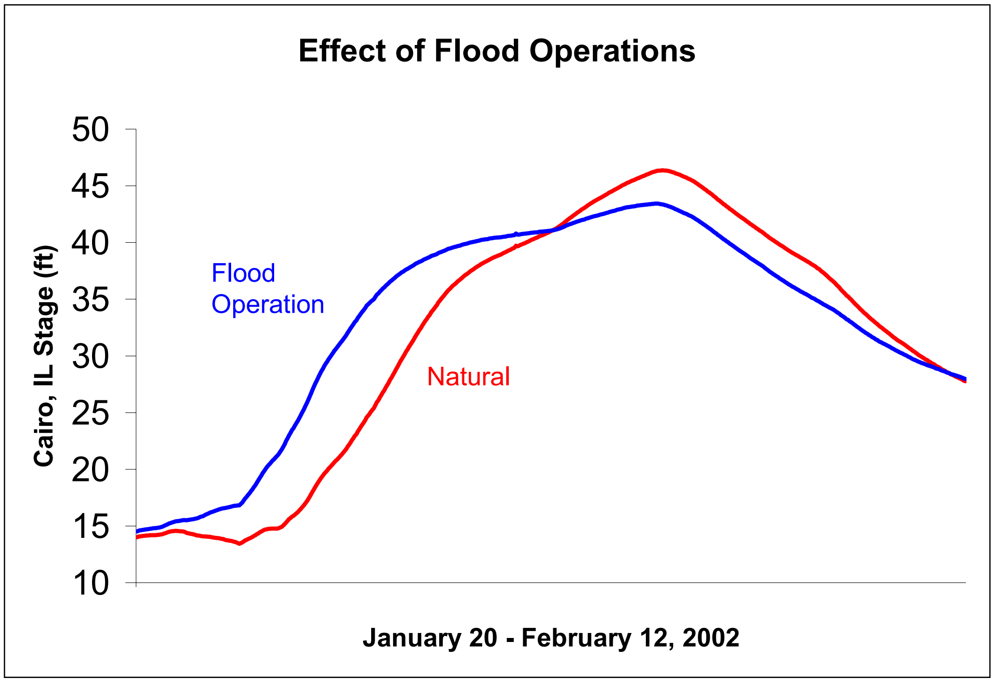

Figure 4. Effect of flood operations at Cairo, IL

Low flows. During low Ohio River flows, operations of the locks and dams cause relatively large fluctuations or 'waves' of flow that are magnified by downstream lock and dam operations. Flows from the Tennessee and Cumberland Rivers also fluctuate due to peaking and ponding operations of Kentucky and Barkley Lakes for hydroelectric power generation. These flow fluctuations cause significant safety and operational problems at Dam 52 and Dam 53, the remaining 1929-era wicket dams. Similar flow fluctuations have been reported for the River Mosel in Germany that also has a series of consecutive navigation locks and dams (Ackermann, et al. 2000). As shown in Figure 5, Cascade is able to model these flow fluctuations.

An optimization process has been included in Cascade to determine lock and dam operations to minimize the flow fluctuations. This feature is continuing to be developed for use in the future to issue operational guidance. It will become of critical importance with the completion of Olmstead Lock and Dam whose operations are expected to create significant flow fluctuations when the modern high lift wicket dam is raised and lowered.

Recently, the value of modeling the river with Cascade during low flows was demonstrated in another way. During the latter half of January 2003, river stages at Cairo, IL began approaching record low levels. This generated a large amount of concern among commercial navigation, the Coast Guard, local water treatment plants, and the USACE Louisville District. However, Cascade's simulations indicated that the Cairo stage was 3 to 5 ft higher than reported by the gage. Upstream of Cairo, Cascade's modeled stages were in good agreement with observed stages. The Team began to suspect that the Cairo gage was not functioning properly and requested that it be checked. On the first two inspections, the gage was reported to be functioning properly. At the Team's insistence, the gage was inspected a third time and found to have a mechanical problem resulting in a gradual increase in error between the actual and reported stage. On January 31st the gage read 7.81 ft, but after repairs, the actual stage was 10.88 ft. Figure 6 shows the Cascade modeled stage compared to the reported stage at Cairo.

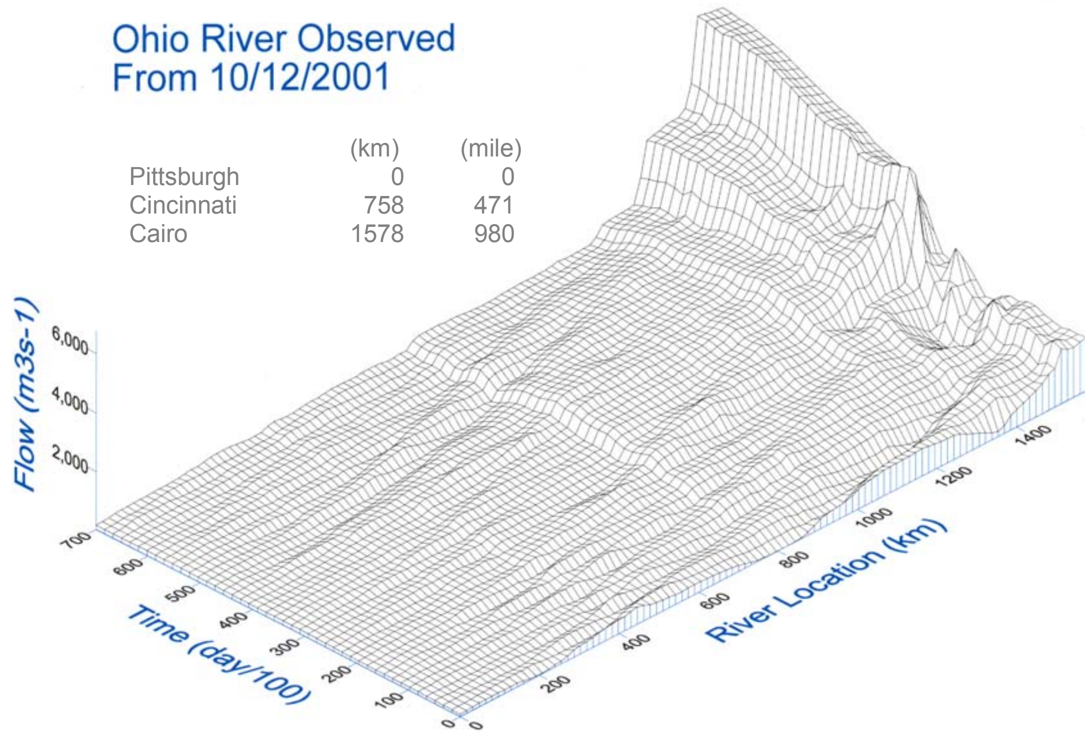

Figure 5. A continuum hydrograph of the Ohio River as hindcast by Cascade

Summary

Cascade is an effective tool for managing the Ohio River and is the culmination of 20 years of dynamic modeling development and operation. It is integral to the conduct of the LRD Water Management Team's responsibilities in flood and low flow management, coordination of public river forecasts, and computation of flood reduction benefits. The model's object-oriented design makes it unique among other existing unsteady flow models, resulting in a highly stable, efficient, and adaptable model capable of simulating the complex dynamic hydraulics of the Ohio River and its junction with the Mississippi River.

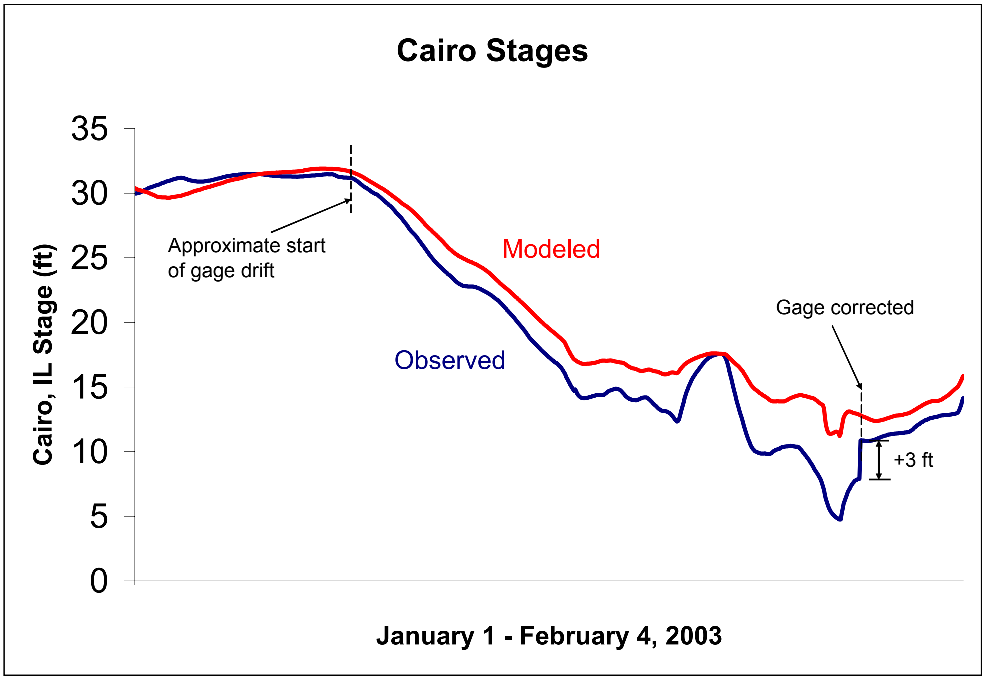

Figure 6. Observed and modeled Cairo, IL river stages

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